A Garnet Tuner for the NOvA Recycler 52.809 MHz RF Cavity

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Table of Contents

Abstract

We describe the function of a yttrium-iron garnet tuner and a radio frequency cavity. This experiment is on the subject of particle acceleration and the role the tuner and cavity play in such. This paper will show the data we received while working with RG 58 coaxial cable models and higher Q transmission line models of the RF cavity and tuner, as well as data from the prototype cavity and the tuner using an adjustable short.

1. Introduction

At Fermi National Accelerator Laboratory (Fermilab), one of the many research programs currently in place is a particle study of neutrinos. Radio frequency (RF) cavities[1] are the preferred means of accelerating these precise particles. The cavities use an electromagnetic standing wave with a frequency set so that it accelerates particles as they pass through. For example, if a series of electron bunches are being accelerated then the sign of the wave will change from positive to negative as the bunch passes through the cavity, switching back to positive as the next bunch arrives. The project to be described in the following paper describes research which studies a garnet tuner and its effects on the resonant frequency cavity.

A tuner is a transmission line that is shorted at one end and loop-coupled to the cavity at the other. In this particular project the tuner is a half-wavelength long (λ/2) and the cavity is a quarter-wavelength (λ/4) long. This tuner has been used to ensure that the temperature variations, RF power levels, and the proton beam intensity stay within a specific range, and do not reach levels that could potentially alter the cavity's results. The tuner maintains the ranges by altering its own electrical length.

A cavity is a coaxial quarter wave resonator with one open end, and the other short-circuited (shorted). The RF cavity and tuner are strongly bonded and as a result, the size of the cavity has to be taken into consideration when doing tests, it is considerably important. The size of a cavity is related to the frequency of the standing wave so that there will be an integer number of nodes throughout the cavity.

During this project coupled electrical circuits and coupled mechanical circuits were tested and used to model the RF tuner. When given a driving force both the coupled mechanical circuit and the coupled electrical circuit reached the same conclusion. When experimenting with this set-up, as the tuner electrical length varied; the frequency, inductance, and capacitance changed as well. With the same set-up, when the mutual inductance (m) of the cavity tuner system was

[1] The prototype radio frequency cavity that will continue to be discussed throughout the entirety of the following paper: 

equal to zero, there was no coupling. As a result all of the information that could be attained from the tuner was excluded.

All of the above experimentation has been and continues to be conducted at Fermilab. Fermilab is a national laboratory that works under the Department of Energy and is dedicated to advancing the understanding of the elementary nature of matter and energy. In order to do so, Fermilab provides leadership roles and resources for skilled researchers to perform basic methodical investigations at the frontiers of high energy physics and similar disciplines of work. Fermilab is located in Batavia, Illinois and is affiliated with other large scale laboratories, including the European Organization for Nuclear Research (CERN). Fermilab is an advanced laboratory committed to many different forms of scientific research, ranging from environmental science to particle acceleration and much more.

Of the particle acceleration programs, the particle study of neutrinos is what we focused on this summer. A neutrino is a member of the Standard Model, belonging to a class of particles known as leptons [2]. The popular belief about neutrinos used to be that they had no mass and retained the ability to move at the speed of light; however, further studies have led to the discovery that neutrinos do indeed possess a miniscule mass of approximately 0.1 eV. With this new understanding, the theory that neutrinos move at the speed of light is proved false as a result of Einstein's theory of special relativity: $\mathrm{E_{Total}} = \gamma \mathrm{m_0 c^2} = \frac{1}{\sqrt{1-\frac{\mathrm{v}^2}{\mathrm{c}^2}}} \mathrm{m_0 c^2}$. This formula states that an object can only truly reach the speed of light if it is free of mass, like photons, the particles which transport light. The total energy needed must be equal to $\gamma m_0 c^2$, meaning that velocity cannot be equal to the speed of light. If velocity were to become equal to the speed of light in this equation, then energy would become infinite; which, in turn, is truly impossible.

Neutrinos have also been found to possess neither a positive nor negative charge, have an angular momentum of ½, and have been proven to be stable particles. Another significant tidbit of information on neutrinos is that, because they belong to the lepton class, they always have a charged partner; the electron, the muon, or the tau. Coinciding with the particle study of neutrinos Fermilab has large and precise detectors sensitive enough to detect the neutrinos when they interact with matter; which seldom occurs. In order to promote an interaction with matter Fermilab builds intense beams that are used to attempt to have the neutrinos travel towards the detectors. This is done through the storage of protons, changing those protons into muons, and therefore resulting in the creation of neutrinos.

Another neutrino experiment being conducted at Fermilab, the Main Injector Neutrino Oscillation Search (MINOS) is designed to study neutrino oscillations. The experiment uses a beam of neutrino particles produced by the Neutrinos at the Main Injector (NuMI) beamline facility. The beam of neutrinos is sent from the MINOS near detector at Fermi National Accelerator Laboratory in Batavia, Illinois to the MINOS far detector at the Soudan Underground Mine State Park in Tower, Minnesota; a 450 mile distance. At Fermilab there are many experiments and projects constantly developing, but the one we are going to acknowledge today is a part of the NOvA (NuMI Off-Axis Electron neutrino Appearance) experiment and focuses on an RF cavity and an yttrium-iron garnet tuner.

2. Materials and Methods

i. *Equipment Used*

a. Network Analyzer[2]

A network analyzer is a scientific instrument used to measure the network parameters of electrical networks; they commonly measure the s-parameters (reflection and transmission) of electrical networks.

b. Oscilloscope[3]

An oscilloscope is an electronic test instrument that enables the observation of constantly shifting voltage signals. Oscilloscopes are typically used to observe the precise wave shape of an electrical signal, its amplitude, distortion, frequency, pulse width and rise time, and the relative timing of two related signals.

c. High Frequency Probe[4]

The high frequency probe we used was an Agilent 85024A probe. The high frequency probe provides passive probing of high impedance circuits.

d. Coaxial Cables[5] and Elbows[6]

The coaxial cables and elbows were used in experimentation when measuring the difference they made in frequency, loss, and Q. The coaxial cables used in our

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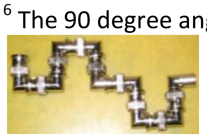
[2] The network analyzer we used for measurements with the model set-ups:  [10]

[3] The type of oscilloscope we used in early set-ups:  [11]

[4] The high frequency probe used in model set-ups:  [12]

[5] The coaxial cables we used for the model set-ups: 

[6] The 90 degree angle elbows that were used during the construction of the cavity and tuner models:



experimentation were RG 58 cables, and can be defined as an electrical cable with an inner conductor surrounded by a tubular insulating layer, surrounded by a tubular conducting shield. A coaxial cable is used as a transmission line for RF signals and has a characteristic impedance of 50 ohms. On the other hand, an elbow is a short section of a 50 ohm coaxial cable with a 90 degree angle used to connect different segments of the λ/2 component of our model set-ups.

e. Adjustable Short[7]

For the adjustable short we used a copper covered piece of stainless steel. This adjustable short was used to help measure the different frequencies associated with the tuner and the RF cavity.

ii. Cavity Dimensions [Not finished—diagram may be useful]

In order to calculate the inner and outer radii the power available, the desired center frequency, and the voltage across the gap needs to be formerly identified. For this specific resonant frequency cavity the power available is 150 kW, center frequency is 52.809 MHz, and the voltage across the gap is 150 kV. The maximum power available to the RF cavity once installed, along with the desired gap voltage determines the shunt impedance (R_{sh}).

To calculate the dimensions of the cavity first you must implement the formula; $\lambda = \frac{v}{f}$[8], which will result in the detection of the full wavelength, furthermore allowing us to calculate the dimensions of the tuner (λ/2) and the cavity (λ/4). In this case v is equal to the speed of light, $c = 2.998 \times 10^8 \frac{m}{s}$, and f is equal to 52.809MHz. However, because we want to ascertain the length of the cavity we must take the full wavelength and divide it by four. $\lambda = 5.677\text{m}$, with this result we found the length of the cavity; $\frac{\lambda}{4} = \frac{5.677\text{m}}{4} = 1.419\text{m} = 56.7\text{in}.$

iii. *Electric Field [Necessary?]*

In the conduction of this project, a section of it required for us to calculate the electric field between the inner and outer cavity when $V = 150kV$[9]. In order to do so we used

[7] The adjustable short used during experimentation inside of a portion of the tuner:  The adjustable short is in the center, between the wide, outer radius, yet outside of the smaller copper radius.

[8] The notation in this formula: λ is wavelength, v is velocity, and f is frequency.

[9] This formula's notation is: V is voltage, and 150 kV is equal to 150 kilovolts.

the formula $V = \int E \cdot dr = \int E(r)\hat{r} \cdot d\hat{r}$, keeping in mind that $E(r) = \frac{E_0}{r} = 882.35\frac{kV}{m}$. After going through the different calculations we came to the conclusion that the electric field between the inner and outer cavity is $E(r,\theta) = \left[\frac{882.35\frac{kV}{m}}{r}\right] \cdot [\sin(\theta)]$, in this formula sin(θ) is not an angle, but representative of …

3. Results

i. Frequency Graphs

The following are graphs illustrating the frequencies received from the models of the cavity and tuner using RG 58 coaxial cables.

(6/1/10) This graph illustrates the resonant frequency measured from a λ/4 (quarter wavelength) transmission line model set-up as shown in Figure 1 using a signal generator **[model #]**, RG 58 coaxial cables, a directional bridge, a short, and an oscilloscope **[model #]** with an input impedance of 1 MΩ. The transmission line length was adjusted by adding 0 to 8, 90° elbows.

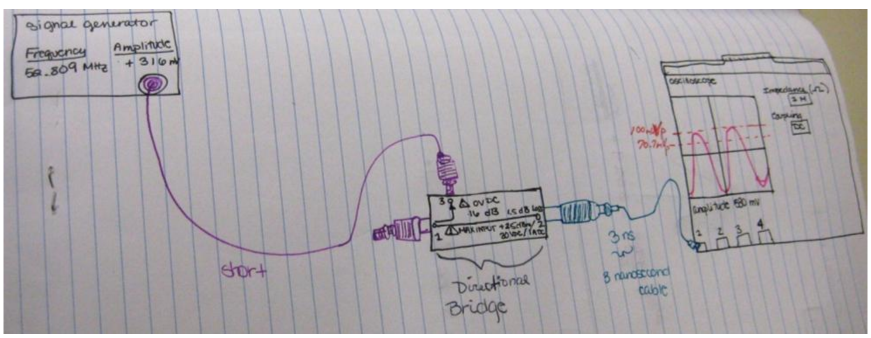
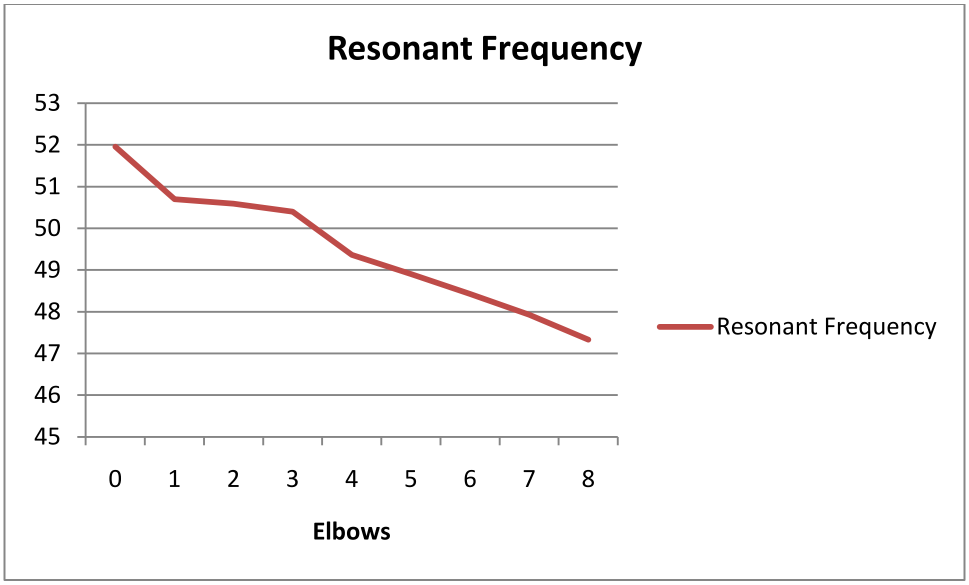


Figure 1



(6/3/10) This graph shows measurements taken in two model set ups; one with the cavity (Figure 3) and one with the tuner (Figure 4). Both set-ups use a network analyzer coaxial cables, shorts, a capacitor, and elbows; however, they are arranged in different manners. **[what was done, what was measured]**

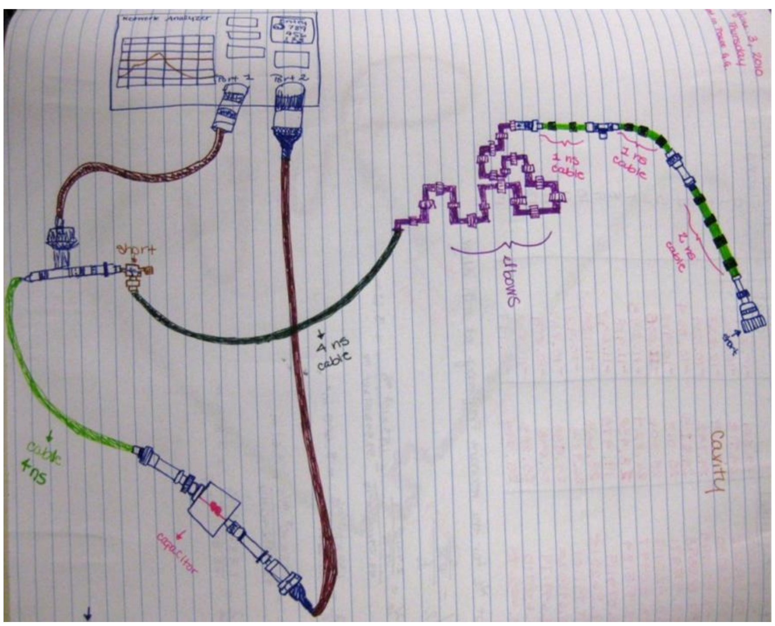


Figure 2

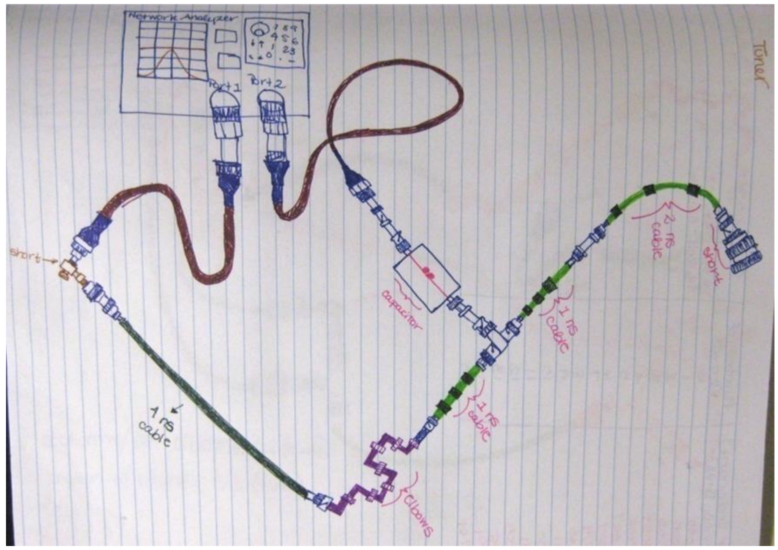
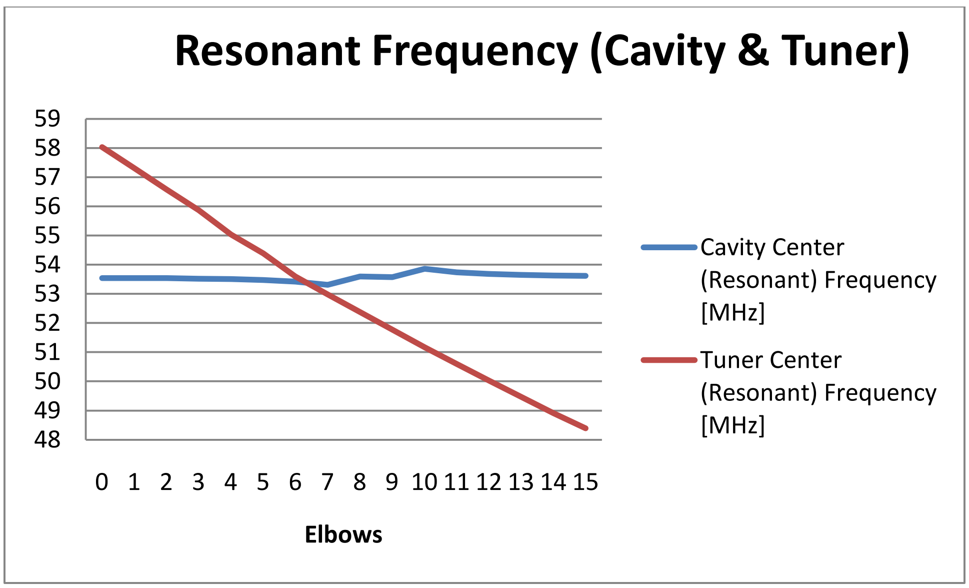


Figure 3



Here is where the set-up transition is made from the use of RG 58 coaxial cables to the use of higher Q transmission lines.

(6/4/10) In this set-up we used the Agilent high frequency probe, shorts, coaxial cables, elbows, and a network analyzer as displayed in Figure 6. The graph shows the measurements of resonant frequency as a function of the number of elbows in circuit sections ① and ②.

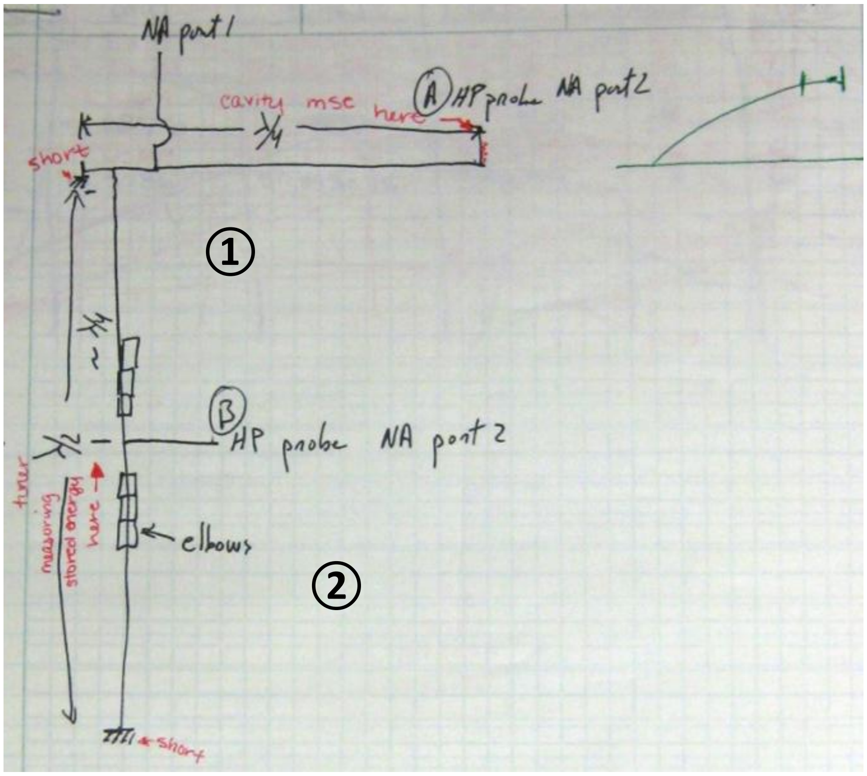
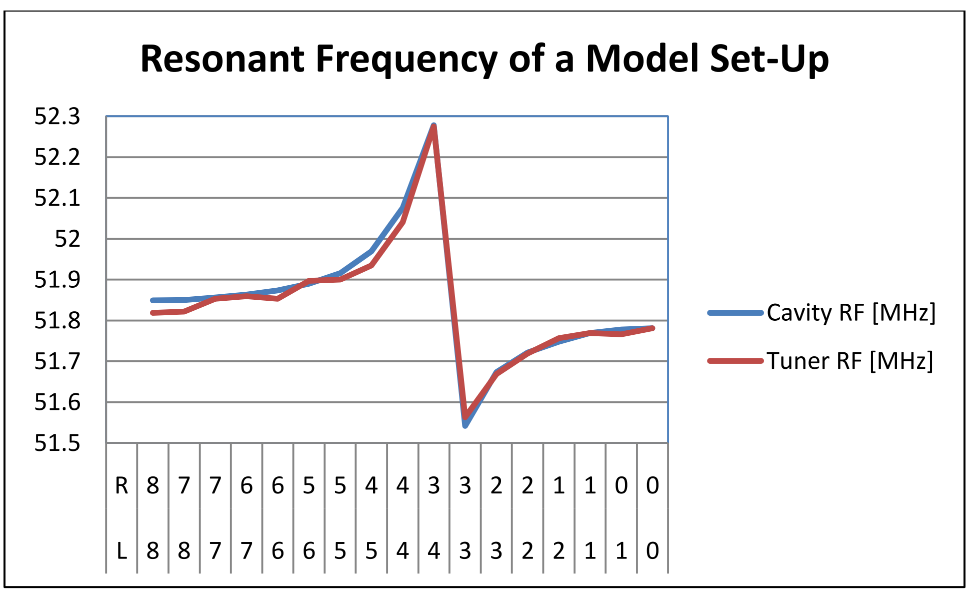


Figure 4



(6/7/10) This set-up is the same set up as before; however, there is an extra tee positioned between two four nanosecond cables. This action positions the short further away from the network analyzer on the λ/2 (half wavelength) side resulting in a slightly different resonant frequency range due to a change in the loop coupling to the tuner. The graph reflects the

measurements of resonant frequency from when there were 16 total elbows, 8 to the left and 8 to the right of the high frequency probe, to when there was a total of 0 total elbows, 0 to the left and 0 to the right.

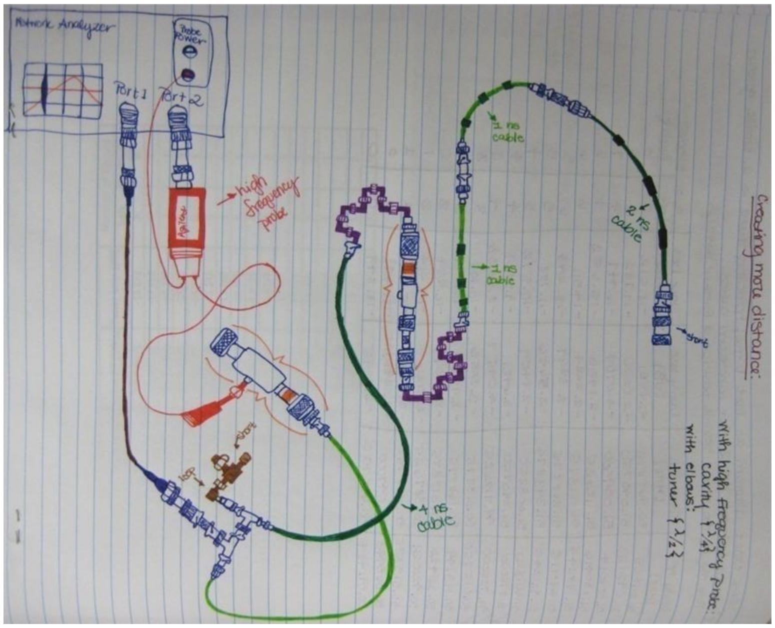
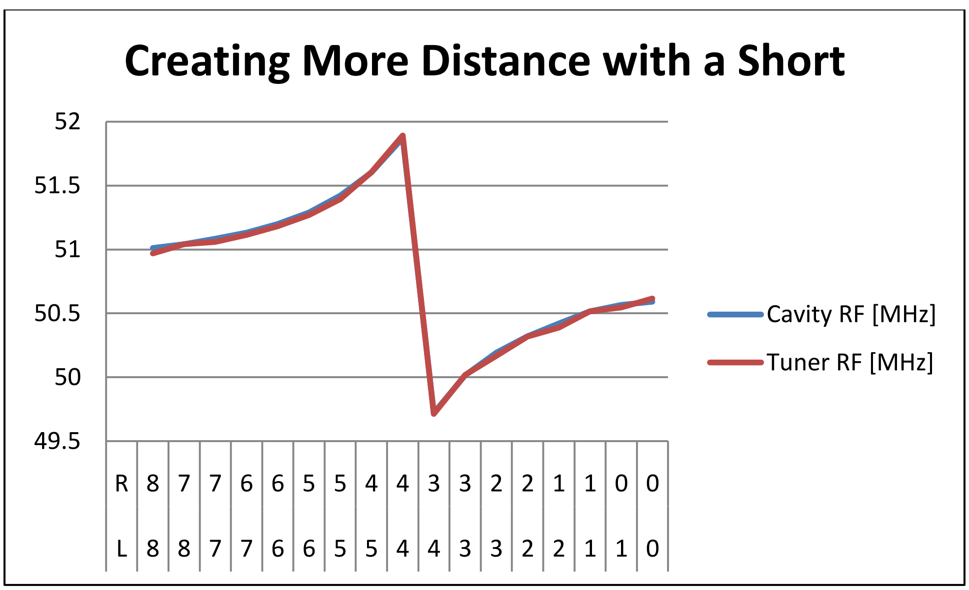
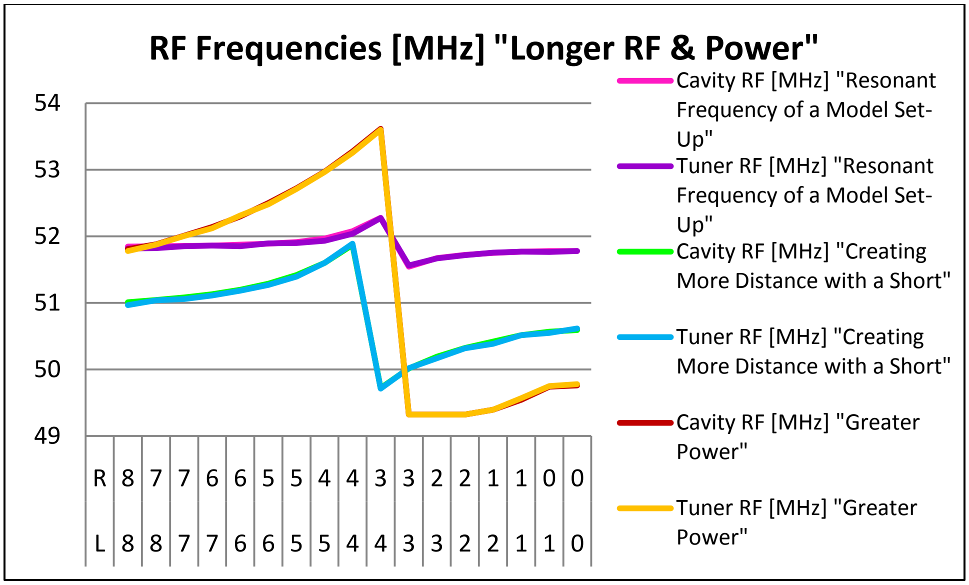


Figure 5



(6/8/10) The graph below shows measurement taken with the set-ups associated with Figures 6 and 7, as well as “Greater Power.”



In the following graphs we make the change from model tests using higher Q transmission lines to model tests by measuring frequencies with the prototype cavity, a 3'/8" EIA transmission line tuner, and an adjustable short.

(6/9/10 & 6/10/10) In the Cable-Model Cavity set-up (Figure 8) we used the network analyzer to provide us with the frequency, among other things, with our model of the tuner and cavity using coaxial cables, a high frequency probe, a capacitor, and several shorts. The Prototype RF Cavity set-up (Figure 9) uses the actual prototype cavity. Here we hooked the tuner to the cavity and took measurements with elbows, a high frequency probe, and a movable short. The following graph is a comparison of the resonant frequency shift measured using the cavity/tuner model (using RG 58 cables) and the actual prototype RF cavity with a 3'/8" EIA transmission line tuner with an adjustable short.

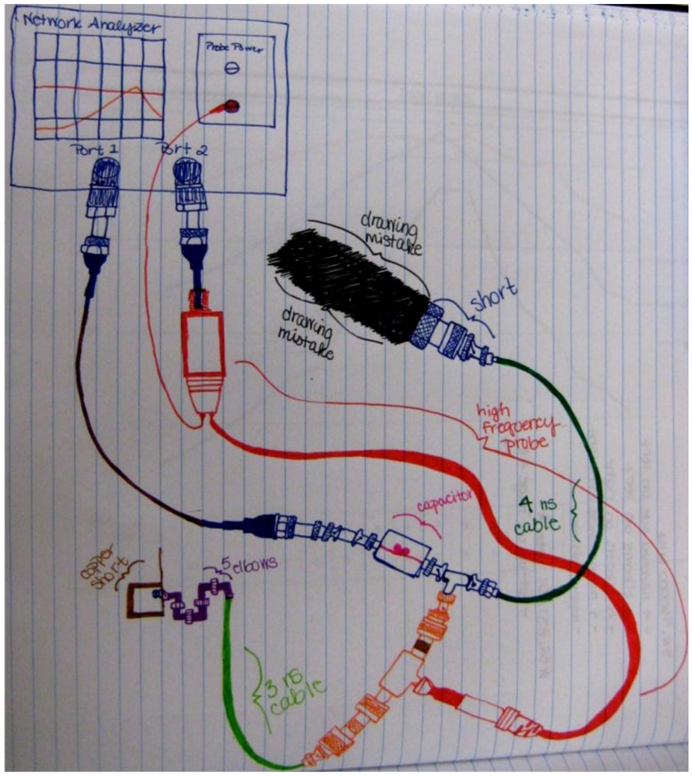


Figure 6

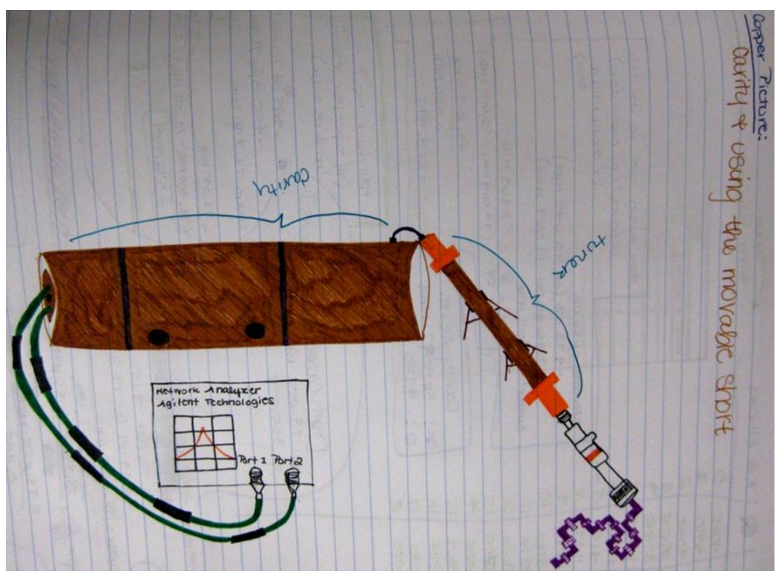
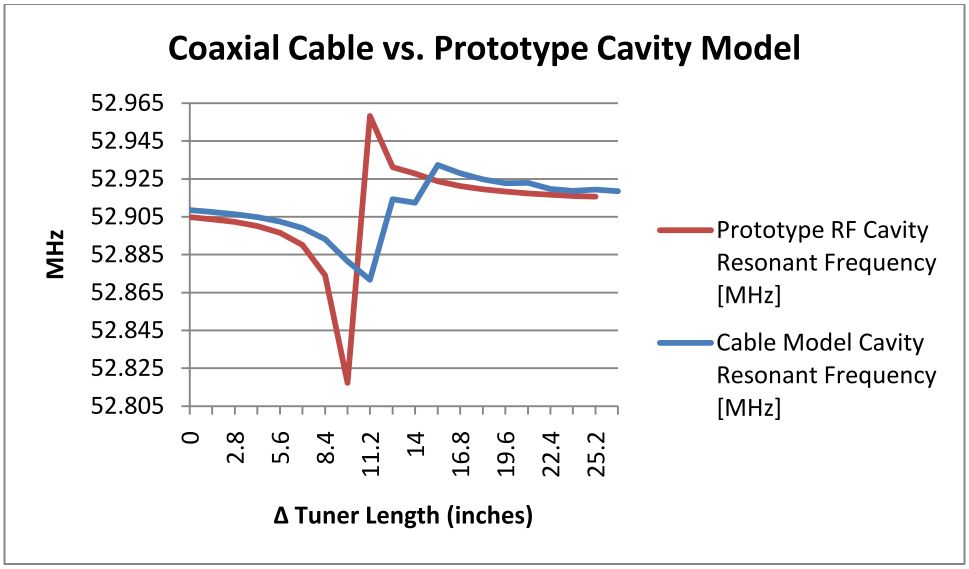
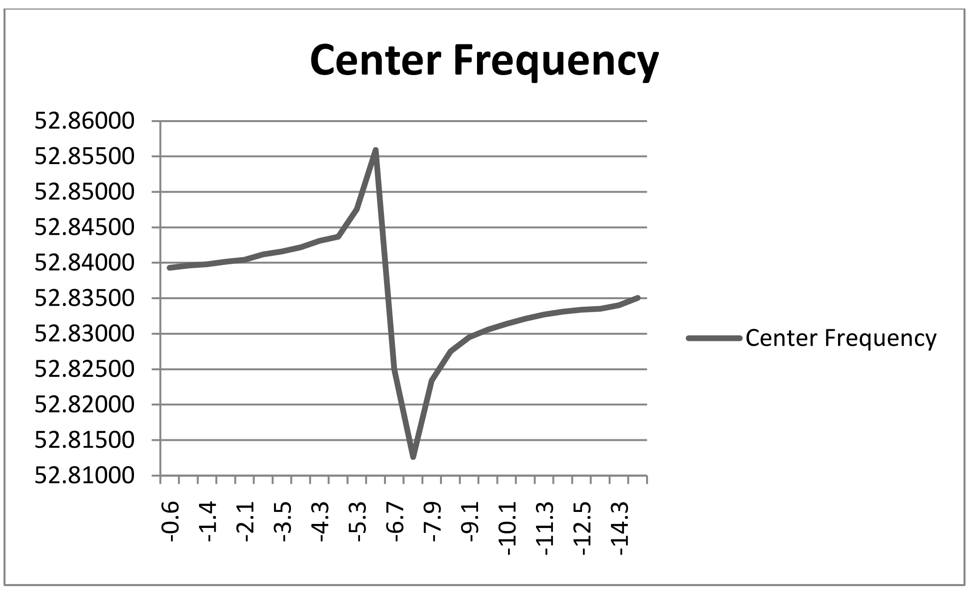


Figure 7



(6/15/10) In this setup the tuner loop was rotated into a different position than in the preceding graph. **[more detail]**



(6/24/10) This set-up displays the frequencies we reached once we solved the for ω_1 and ω_2 from Figure 10. **[more detail…explain the formula]**

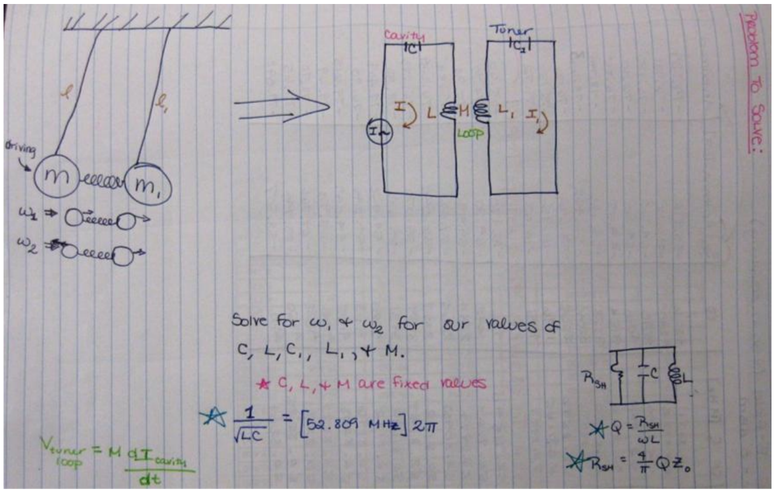
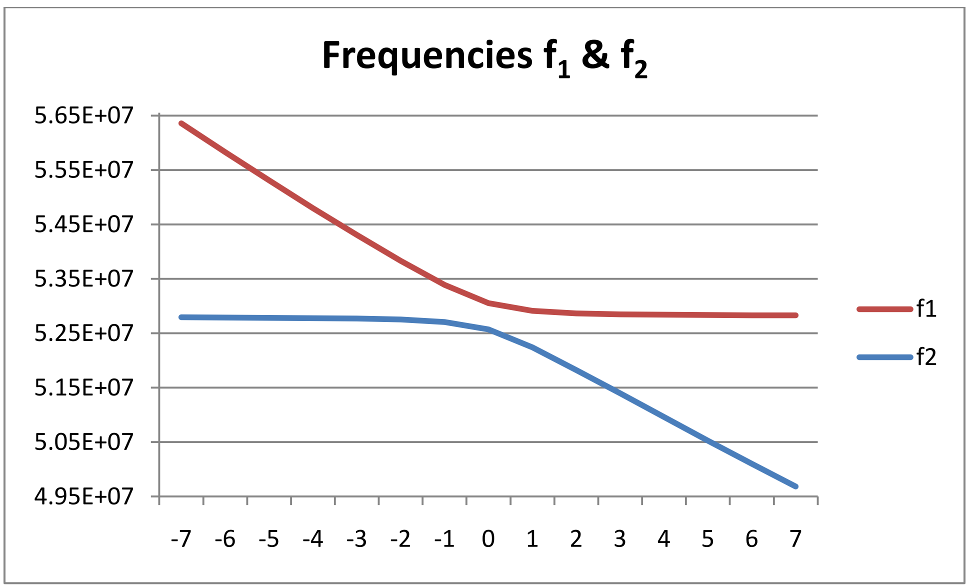
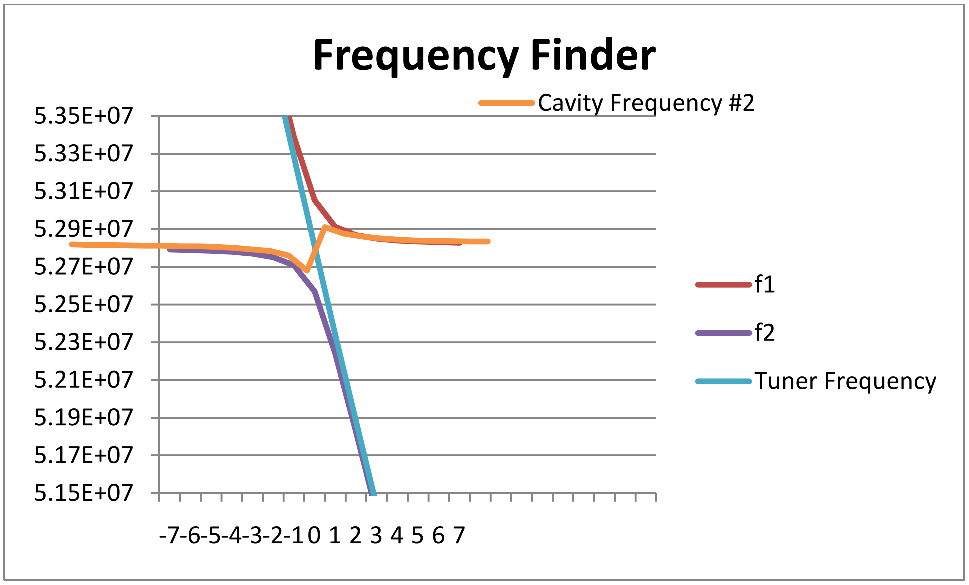


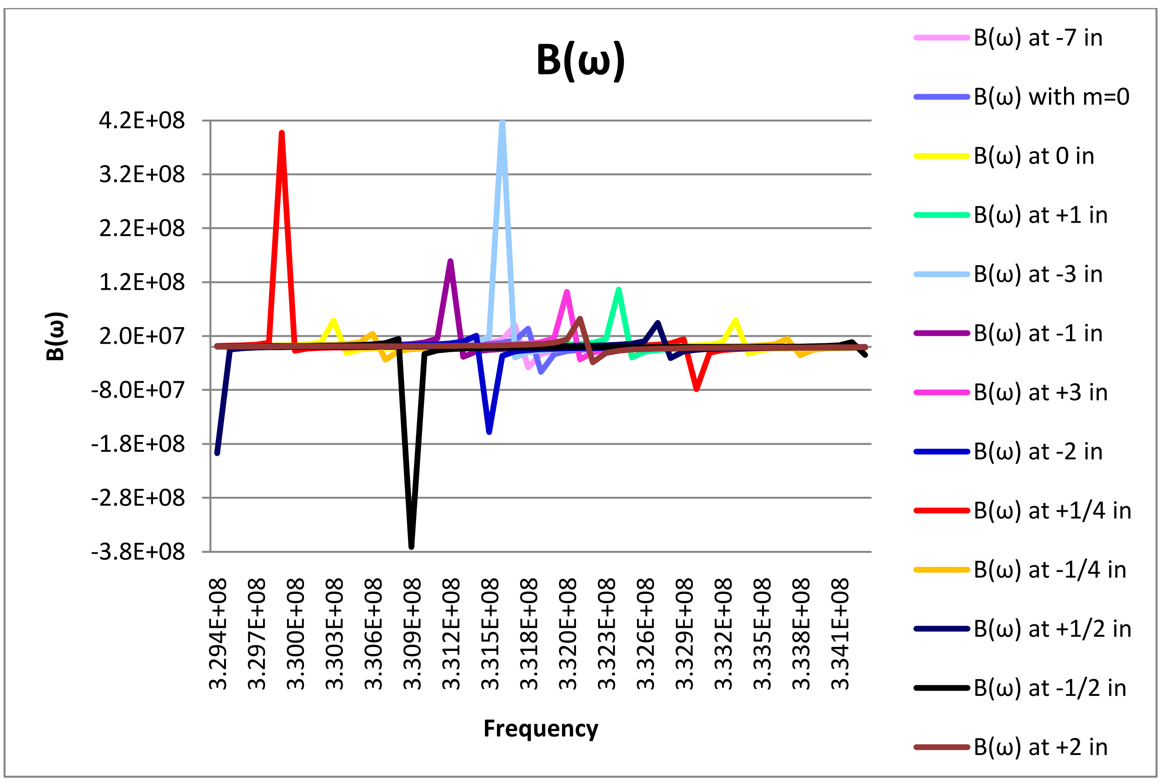
Figure 8



*(6/24/10 & 6/25/10)**** This graph includes the frequencies, f_1 and f_2 from the above graph along with the graphs of the resonant frequencies of the tuner and the cavity once we came to a conclusion of the afore-mentioned formulas. **[more detail]**

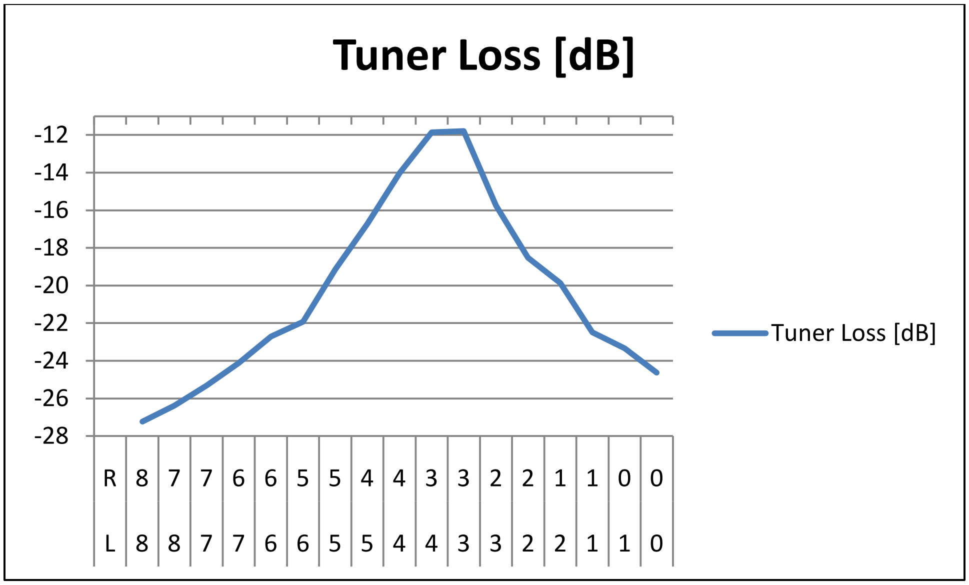


(6/30/10—7/1/10—7/2/10) This graph is the combination of all of the B(ω) graphs. We came to receive B(ω) from the former formulas when solving for $I = Acos(\omega t) + Bsin(\omega t)$, when solving for B(ω) at several different lengths.

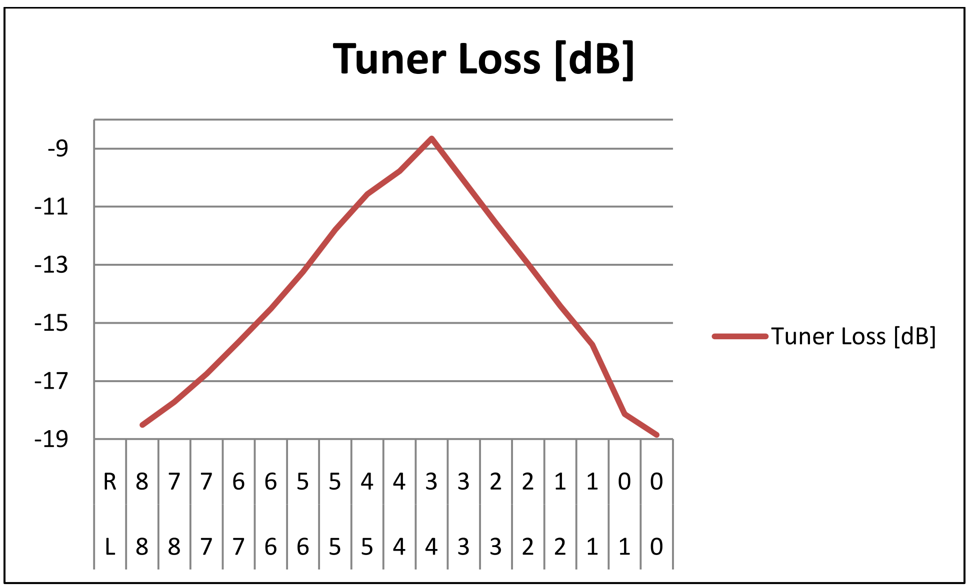


ii. *Tuner Loss*

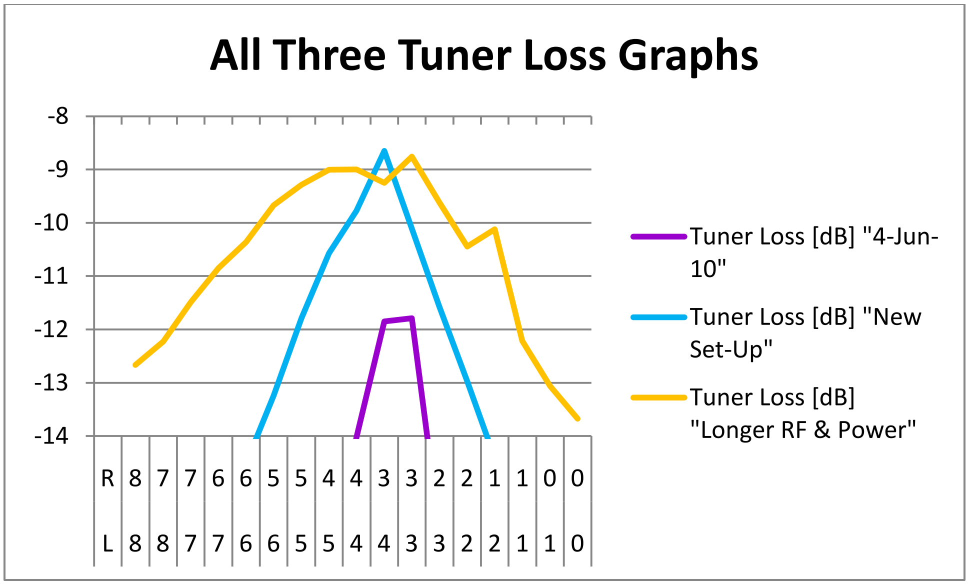
(6/4/10)



(6/7/10)

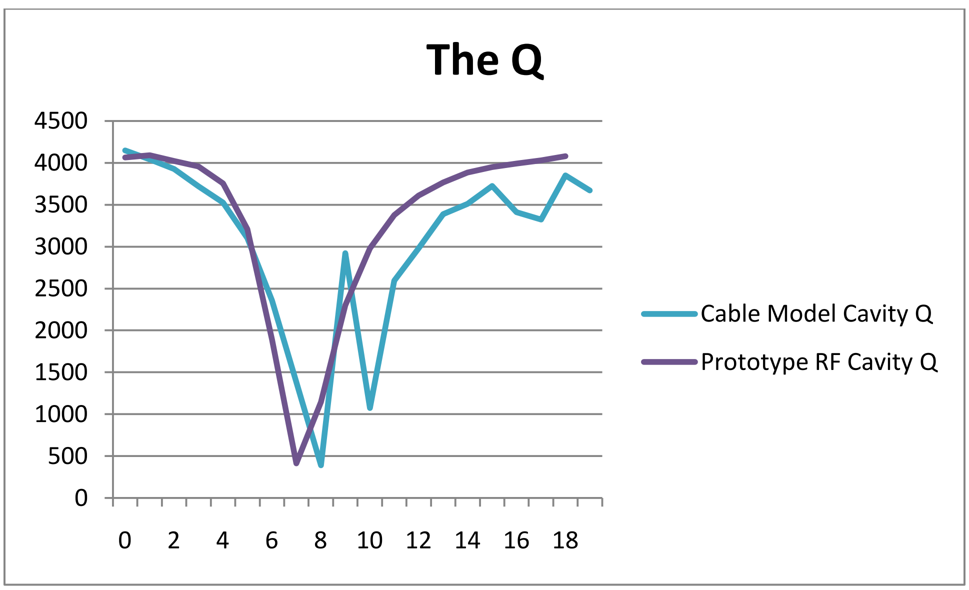


(6/8/10—Tuner Loss Graphs (all 3))

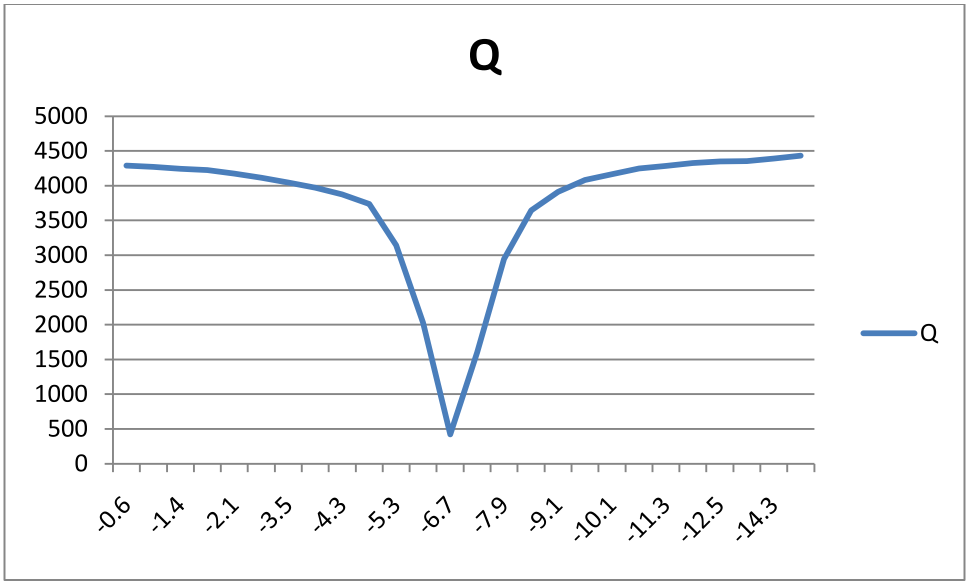


iii. *Q*

(6/9/10 & 6/10/10)

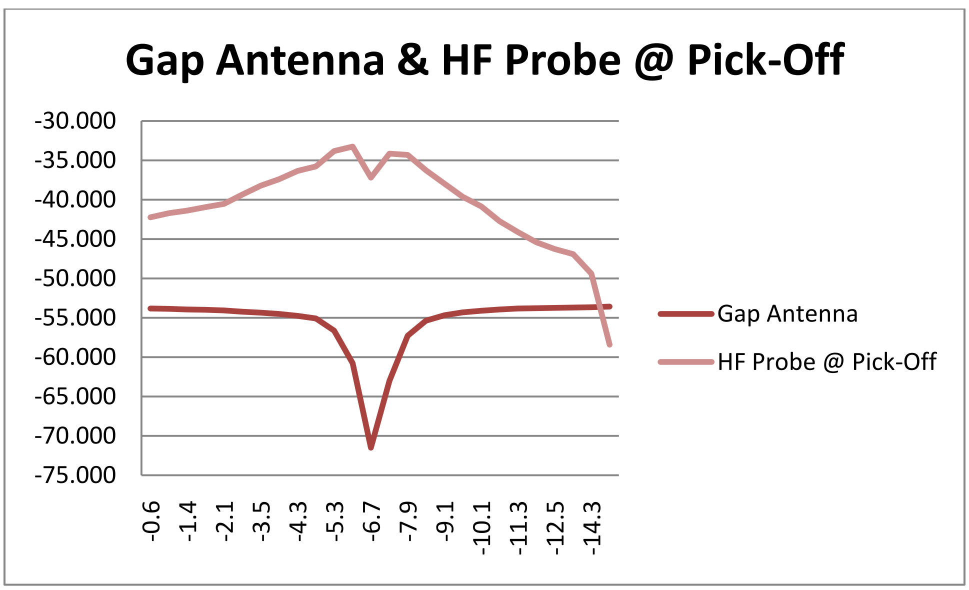


(6/15/10)

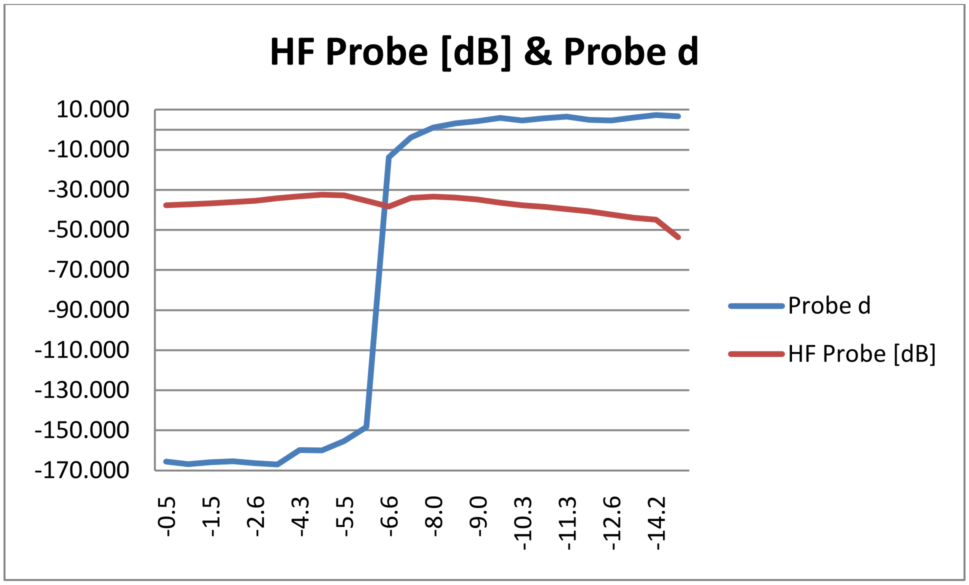


iv. Other

(6/15/10)



(6/16/10)



v. *3 Graphs with respect to $I_{monitor}$ (Amps)*

a. *Frequency*

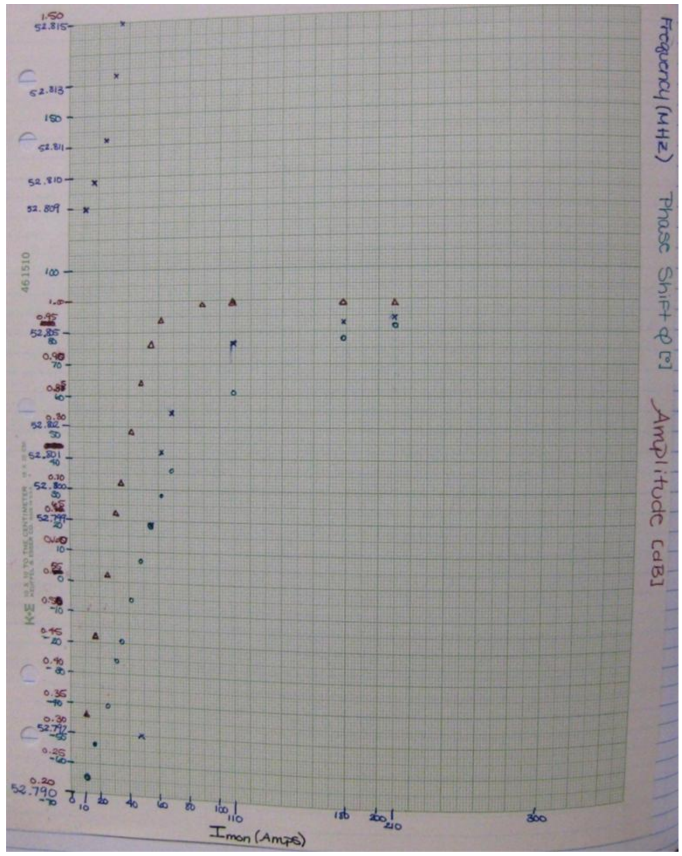
In this graph we measured frequency [MHz] as a function of the monitors' current [Amps]. This graph was used to determine loss [dB] and where the loss is the least.

b. *Phase Shift*

This graph measures the phase shift [ϕ] of the cavity when the tuner was connected as a function of the monitors' current [Amps] while it examines the changing of the bias of the solenoid. This graph measures the variance of the voltage and amperes.

c. *Amplitude*

This graph measures the amplitude [dB] of the 52.809 MHz cavity over a tuning range of 5-10 kHz as a function of the monitors' current [Amps]. This graph was based off of a logarithmic magnitude graph and changes with the initial variance of voltage and amperes.



4. **Discussion [Don't go back and tell what was done, but describe my interpretation of the results and if there was anything I wanted them to do…was I looking for something….say how well the results came out and explain the results….my interpretation of the charts…what conclusion can I draw from the graphs]**

During the summer 2010 internship models of the cavity and tuner using RG 58 coaxial cables were made, as well as models with higher Q transmission lines. Tests using both the prototype cavity and the tuner were also performed. In performing each of these actions information of resonant frequencies, different Q's, and loss was received.

When beginning with the RG 58 coaxial cable models I began to learn how to use a network analyzer and the importance, as well as the function of an RF cavity and tuner. The models gave me a sense of what was yet to come.

After working with solely the RG 58 coaxial cables, I began to use high Q transmission lines and a high frequency probe. This led to explanations about ports, calibration, and power. Once these models became significant enough I began to go to Meson to work with the prototype cavity, the tuner, and the adjustable short.

Once the tests progressed to Meson, work with the actual prototype cavity and tuner began to commence. While working with these there was a better opportunity to understand the garnet tuner for the NOvA recycler. The tests we performed with the cavity and the tuner in Meson were to determine which specific set-up would provide the right frequency that we were looking for.

What we did:

a) Made models with RG 58 coaxial cable
b) Made models with higher Q transmission lines
c) Did tests with the cavity
d) Did tests with the tuner

5. Conclusion

We have run tests with the prototype resonant frequency cavity with a garnet tuner to show how the resonant frequency, the Q, and tuner loss change with different set-ups and tuner lengths. Many testes were run during the past eleven weeks and throughout their execution advantageous results were attained as well. It would be beneficial if more tests are performed, as is planned, in order to receive more accurate results and to learn more of the garnet tuner and the cavity.

6. Acknowledgments

This research was conducted at Fermi National Accelerator Laboratory in Batavia, Illinois. I thank Dianne Engram, Jamieson Olsen, Linda Diepholz, Sandra Charles, and the rest of the SIST committee for the opportunity to participate in such a prestigious internship. I also thank them for their open-door policies and being of great assistance to me whenever I was in need. With genuine gratitude I would also like to thank my supervisor, Dave Wildman, for having such patience and leading me through each process so that I could emerge from this program with a greater knowledge of physics and one of its many detailed applications. I would also like to thank my assistant supervisor, Robyn Madrak, for also being there to help me through this process and for helping to explain some concepts in more detail when it took me a little longer to understand.

I would also like to thank my summer mentor Cosmore Sylvester for being there to make sure that everything was going as planned and that I was headed in the right direction. Thank you to Dr. James Davenport for being so open, helpful, and kind when it came to the development of this final paper and life in general3n. Thank you to everyone in the Southwest Annex, you made me feel extremely welcome and I enjoyed coming to work every week even more because you all were always there to say good morning and to chat about work, progress, and life.

And in conclusion, I would like to thank the Almighty for watching over me and guiding me along the road of life.

7. References

[1] Fermi National Accelerator Laboratory, “Neutrino Oscillations.” [Online]. Available: http://www-numi.fnal.gov/public/oscillations.html. [Accessed: Jul. 13, 2010].

[2] Fermi National Accelerator Laboratory, “Neutrinos.” [Online]. Available: http://www-donut.fnal.gov/web_pages/neutrinospg/Neutrinos.html. [Accessed: Jul. 13, 2010].

[3] London’s Global University, “R-F Cavities.” [Online]. Available: http://www.hep.ucl.ac.uk/undergrad-projects/3rdyear/PPguide/rfcav.htm. Accessed: [Jul. 13, 2010].

[4] Fermi National Accelerator Laboratory, “What is Fermilab?,” *About Fermilab*, Feb. 27, 2001. [Online]. Available: http://www.fnal.gov/pub/about/whatis/mission.html. Accessed: [Jul. 13, 2010].

[5] Fermi National Accelerator Laboratory, “MINOS for the Public,” *Main Injector Neutrino Oscillation Search*. [Online]. Available: http://www-numi.fnal.gov/PublicInfo/index.html. Accessed: [Jul. 13, 2010].

[6] Fermi National Accelerator Laboratory, “The MINOS Experiment and NuMI Beamline,” *Main Injector Neutrino Oscillation Search*. [Online]. Available: http://www-numi.fnal.gov/. Accessed: [Jul. 13, 2010].

[7] Argonne National Laboratory, “Ask A Scientist©.” [Online]. Available: http://www.newton.dep.anl.gov/askasci/phy99/phy99186.htm. Accessed: [Jul. 14, 2010].

[8] A. Erzberger, “Conservation Laws,” Mar. 18, 2002. [Online]. Available: http://quarknet.fnal.gov/toolkits/ati/conservation.html#leptons. Accessed: [Jul. 14, 2010].

[9] S.M. Hanna, E. Privit, and J. Keane, “YIG Tuners for RF Cavities,” *IEEE Transactions on Magnetics*, vol. 28, pp. 3210-3212, Sept. 1992.

Picture References:

- http://www.home.agilent.com/agilent/techSupport.jspx?pid=1350013&cc=US&lc=eng&t=80045.k.1&guid=181646 [Network Analyzer] [10]
- http://www.pd.infn.it/elettronica/Strumenti/Immagini/MSO4104.JPG [Oscilloscope] [11]
- http://www.surplussalesline.com/detail.asp?ProdID=6560 [High Frequency Probe] [12]

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